AD-751 782

EVAPORIMETRY IN THE CANAL ZONE. PART I. CLIMATOLOGICAL MEASUREMENTS OF EVAPORATION

Wilfried H. Portig

Army Tropic Test Center
APO New York, New York 09827

April 1972

9 1

AD ______________________

TECOM PROJECT NO. ______________

USATTC REPORT NO. 7204004

ARPA ORDER NO. 740

OCRD PROJECT NO. 2M025001A724 01

EVAPORIMETRY IN THE CANAL ZONE

PART I

CLIMATOLOGICAL MEASUREMENTS OF EVAPORATION

TECHNICAL RESEARCH NOTE
BY
WILFRIED H. PORTIG
APRIL 1972

UNITED STATES ARMY TROPIC TEST CENTER
FORT CLAYTON, CANAL ZONE

29

DISPOSITION INSTRUCTIONS*

Destroy this report when it is no longer needed. Do not return it to the originator.

DISCLAIMER

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents. The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or software. This report may not be cited for purposes of advertisement.

A

*These disposition instructions do not apply to the record copy (AR 340-18).

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Commanding Officer US Army Tropic Test Center Fort Clayton, Canal Zone	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
Evaporimetry in the Canal Zone
Part I: Climatological Measurements of Evaporation

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Special Report - Part I (1965 through 1969)

5. AUTHOR(S) (First name, middle initial, last name)
Wilfried H. Portig

6. REPORT DATE April 1972	7a. TOTAL NO. OF PAGES 30	7b. NO. OF REFS 9

8a. CONTRACT OR GRANT NO. ARPA Order No. 740 b. PROJECT NO. OCRD Project No. 2M025001A724 01 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) USATTC Report No. 7204004 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency and Army Research Office of the Office of the Chief, Research and Development

13. ABSTRACT

The United States Army Tropic Test Center made measurements of 24-hour totals of evaporation during conduct of the Environmental Data Base Project in the Panama Canal Zone from 1965 to 1969. In this report measurements obtained with Piche evaporimeters are compared with those made simultaneously with the Standard Pan at the same locations. The Standard Pan often produced invalid data because of splash-out during tropical rain and, although an international standard, proved less reliable than the Piche.

The annual variation of the measurements is presented for open terrain as well as for different heights in and above a forest.

Ia

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Humid Tropics						
Tropical Environment						
Canal Zone						
Climate						
Environmental Data Base						
Micrometeorology						
Evaporation						
Meteorological Instruments						
Evaporimeter						
Piche Evaporimeter						
Standard Evaporation Pan						
Tropical Rainfall						

Ib

ABSTRACT

The United States Army Tropic Test Center made measurements of 24-hour totals of evaporation during conduct of the Environmental Data Base Project in the Canal Zone from 1965 to 1969. In this report measurements obtained with Piche evaporimeters are compared with those made simultaneously with the Standard Pan at the same locations. The Standard Pan often produced invalid data because of splash-out during tropical rain and, although an international standard, proved less reliable than the Piche.

The annual variation of the measurements is presented for open terrain as well as for different heights in and above a forest.

FOREWORD

During the years 1965 through 1969 the United States Army Tropic Test Center conducted a project in the Canal Zone entitled "Environmental Data Base for Regional Studies in the Humid Tropics." It was sponsored by the Advanced Research Projects Agency and Army Research Office of the Office of the Chief of Research and Development. Among other parameters, evaporation was recorded. Analysis of these evaporation data is being published in two parts under the common title "Evaporimetry in the Canal Zone." This report is Part I.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION A. DETAILS OF INVESTIGATION

1. INTRODUCTION

This report describes, scrutinizes, and condenses routine measurements made from 1965 through 1969 during the Environmental Data Base Project. It is primarily aimed at filling gaps in world-wide surveys of evaporation. Both classes of such surveys, whether based on the Standard Pan evaporimeter or on the Piche evaporimeter, can profit from this information. Researchers who are involved in relating these two types of evaporation measurements should find material useful for their work. In addition, climatological information is offered that presents the vertical and seasonal variation of evaporation within a tropical forest.

2. BACKGROUND

Evaporation is the process through which water is transferred from the liquid state into vapor. It is accompanied by a conversion of sensible heat into latent heat, which is stored in the vapor and can be retransformed into sensible heat when and where the vapor is retransformed into ice or liquid water. This combination of two physical processes is of greatest importance in natural phenomena, including those situations in which man modifies nature.

Evaporation is essentially the last stage in the water cycle of plants (where it is called transpiration). It is important in the heat regulation of man, animals, and machines. It is one of the links that brings the water from the oceans and other water surfaces to remote areas where it leads to cloud formation and precipitation.

Unfortunately, there seems to be no way to measure natural evaporation without altering it, and Berényi (1) assumes that there will never be a way. Some simple and inexpensive evaporimeters have been developed and are in wide use. More sophisticated instruments, "lysimeters," yield more realistic results, but are expensive and difficult to handle. Consequently, few of them are used. The instruments of the inexpensive category have in common a continuous water supply (i.e., the water is replenished before it is exhausted). Evaporation from oceans and other open water surfaces, and to a certain degree from the human skin, is a natural process that matches the water supply principle of such evaporimeters. Other natural processes such as evaporation from soil deviate substantially from this principle, and evaporimeters show especially high values of evaporation in desert areas where natural evaporation is close to zero. On the other hand, steam rising from a hot pavement after a shower, or from a warm water surface, is proof that evaporation can take place even into saturated air where the vapor must condense and becomes visible. An evaporimeter does not indicate any evaporation in such a case.

Many series of evaporation measurements have been accumulated during the last hundred years. Two of the most preferred evaporimeter types are the Piche evaporimeter (called by some authors "atmometer") and the Standard Pan. The latter has been recommended by the World Meteorological Organization and is mandatory for NOAA/Weather Bureau stations. It is shown in the following discussion that there are situations in which measurements with the Pan are impossible while the Piche instrument remains operable. This report does not deal with the meaning of the measurements, which will be published as Part II, "Comparisons of Various Types of Evaporimeters on an Hourly Basis," at a later date.

3. OBSERVATION SITES

The evaporation measurements described and summarized in the last part of this report were made at the two main sites of the Environmental Data Base Project and at one site maintained by the Panama Canal Company (figure 1). The geographical coordinates of the three sites are:

Albrook (semievergreen forest)	09°01'N, 79°33'W, 31 meters MSL
Chiva Chiva (grassland)	09°01'N, 79°35'W, 30 meters MSL
Madden Dam (river slope)	09°13'N, 79°37'W, 90 meters MSL

For the first two sites the full observation protocols are available. For Madden Dam only the results of the computations exist. It was possible to correct many errors in the records of Albrook and Chiva Chiva sites and either to eliminate such data or to replace them with estimated values.

4. AVAILABLE DATA

Table I lists the periods and locations for which routinely made 24-hour evaporation totals are available and the type of instrument which was used.

TABLE I. LOCATIONS, TIME PERIODS, AND HEIGHTS FOR WHICH DAILY EVAPORATION TOTALS ARE AVAILABLE

	CHIVA CHIVA (open site)		ALBROOK (forest site)					MADDEN DAM (open site)
	Height in Meters		Height in Meters					Height in Meters
	0.5		0.5		13.5	28.5	46	0.5
1965								
May-Aug	-	Pi	-	Pi	Pi	Pi	Pi	-
Sep	-	Pi	-	Pi	Pi	-	-	-
Oct	SP	Pi	-	Pi	Pi	Pi	-	-
Nov	SP	Pi	SP	Pi	Pi	-	-	-
Dec	SP	(Pi)	SP	Pi,(C)	Pi	-	-	-

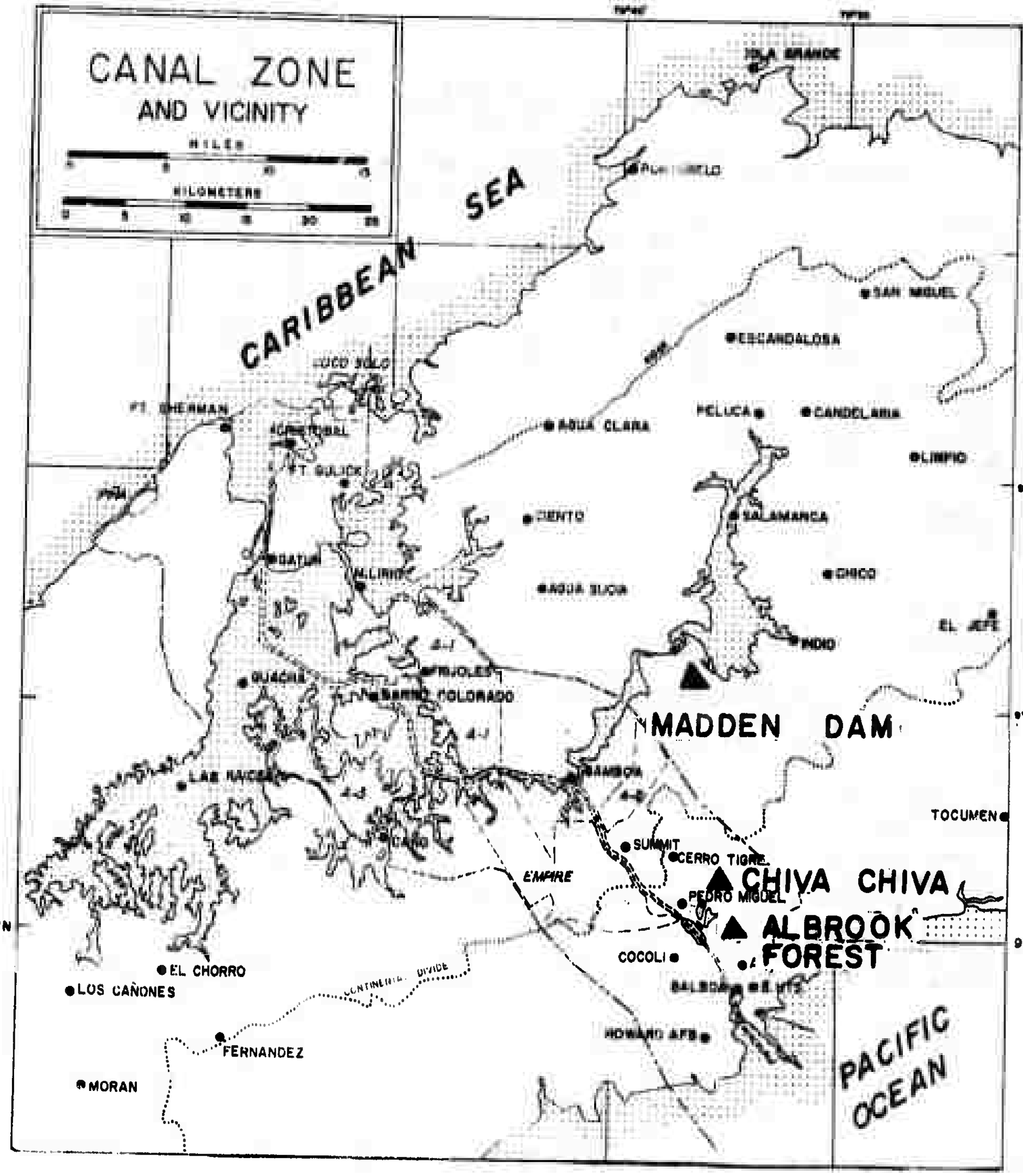
Table I (concluded)

	CHIVA CHIVA (open site)		ALBROOK (forest site)					MADDEN DAM (open site)	
	Height in Meters		Height in Meters					Height in Meters	
	0.5		0.5		13.5	28.5	46	0.5	
1966									
Jan	SP	-	SP	Pi, C	Pi	-	-	-	
Feb-Mar	SP	Pi	SP	Pi	Pi	-	-	-	
Apr	SP	Pi	SP	Pi	(Pi)	(Pi)	(Pi)	(SP)	(Pi)
May-Nov	SP	Pi	-	Pi	-	Pi	Pi	SP	Pi
Dec	SP	Pi	-	Pi	(Pi)	Pi	Pi	SP	Pi
1967									
Jan-Apr	SP	Pi	-	Pi	(Pi)	Pi	Pi	SP	Pi
May-Dec	SP	Pi	-	Pi	(Pi)	Pi	Pi	-	
1968									
Jan	SP	Pi	-	Pi	Pi	Pi	Pi	-	

LEGEND:
SP = Standard Pan
Pi = Piche evaporimeter
C = Piche evaporimeter under cover
() = Incomplete data

The Standard Pan is a flat-bottomed cylinder of zinc-coated steel, 1 foot high and 4 feet in diameter, which stands on a support of wooden logs. It is almost completely filled with water. Changes in the height of the water level are measured with a precision instrument, called a hook gage, and these changes are supposed to reflect evaporation and precipitation. Unfortunately, they also reflect contamination by solid matter, splash-out through weather effects, and occasionally animal activity. Animals and larger pieces of solid matter can be kept off the Pan by placing it in a cage of chicken wire. Such a cage reduces the effects of wind as well as radiation, but these reductions are considered to be negligible.

In the observations under discussion here, the splash-out through weather effects proved to be frequent and of such a magnitude that many measurements are completely wrong. Splash-out can be produced by high winds and by heavy rain. High winds occur in the Canal Zone for brief periods only at the onset of thunderstorms, and no evidence for wind-produced splash-out could be gathered. However, splash-out caused by large drops during heavy rain proved to be such an important factor that a substantial percentage of Pan evaporation measurements were discarded. Whenever splash-out occurs, it appears in the measurements in the same way as does an increase in evaporation. Thus, surveys computed from



LEGEND: △ Evaporimeter Site

– – – – Border between Canal Zone and Republic of Panama

▬▬▬▬ Panama Canal

Figure 1. Locations of the Three Evaporimeter Sites

unchecked Pan measurements may yield erroneously high values of evaporation. Table II, together with the information that 10 to 30 percent of Pan measurements are invalidated by splash-out, demonstrates the low level of accuracy of published evaporation averages obtained from Standard Pan measurements during the rainy season. Most averages will be excessively high. In a rainy climate another fact reduces the accuracy even further. The rainfall is traditionally measured with an accuracy of one-tenth of that of evaporation (hundredth versus thousandth of an inch). The hundredths are doubtful in cases of heavy rain because the recording paper may warp, the recording curve may become very thick, the mechanism may not be able to follow the impulses in proper form, etc. The rainfall total measured in such an inaccurate way must be subtracted from the water level change in the Pan to obtain the amount of evaporation. Six out of 34 measurements at the end of the 1965 rainy season were discarded because the computation resulted in negative evaporation which in those cases appeared unrealistic.

The Piche evaporimeter is a vertical, water-filled glass tube of 1.3 centimeters inner diameter. From this tube, water evaporates through a circular piece of blotting paper of 3.2 centimeters in diameter attached to the lower end of the tube. A scale etched into the glass permits measurements of the changes of water level. The Piche instrument is less affected by rain than the Standard Pan; in some cases the surface tension of the water at the surface of the blotting paper changes during rain so that the water actually rises (against gravity) in the tube. This effect may be enhanced by the rain cooling the tube, the water, and the vapor above the water column. These effects can be computed to be small, and being partly reversible they can be disregarded. High winds can produce a splash-out from the Piche when a gust shakes the instruments enough to cause the blotting paper to drip. No numerical values of gust effects of the Piches of this study are available, but they are assumed to be close to zero. This assumption has its justification not only in the infrequency of gusts in the Canal Zone, but also in the fact that the Piche tubes were secured against swinging by means of a stabilizing arm holding the tube at a constant distance from its stand.

Table II shows the influence of rain on evaporation measurements. The Piche displays, as seems to be natural, a decrease of evaporation with increasing rain and its standard deviation from the average stays constant. This can be interpreted as a sign that real evaporation has been measured. The Pan shows the expected decrease of evaporation with slightly increasing rain, the standard deviation staying almost constant. With above half an inch of rain in 24 hours, however, the measurement rises instead of falling and so does the standard deviation. Before the statistics were computed, it was necessary to discard 10 out of 68 days because the Pan showed condensation rather than evaporation. It is concluded from table II that Pan measurements are erroneous on days with intense ("tropical") rainfall.

TABLE II. DAILY PAN AND PICHE EVAPORATION AT CHIVA CHIVA OPEN SITE [MEAN ($\bar{x}$) AND STANDARD DEVIATION (σ)]

24-hour Rainfall (inches)	0-0.02		0.03-0.49		0.50 and more	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Piche (milliliters)	2.38	$\pm$0.97	1.70	$\pm$1.02	1.41	$\pm$1.00
Pan (inches)	0.121	$\pm$0.063	0.096	$\pm$0.073	0.173	$\pm$0.137
Number of days (Period: 7 Oct - 13 Dec 65)	19		20		19	

Attempts to use the Standard Pan in the forest were almost completely unsuccessful. There are two major obstacles to a reasonable interpretation of Pan data in the forest. First, a great quantity of debris (leaves, buds, insects) falls into the Pan and raises the water level not only by its own mass but also by the water it may carry after rain. Second, forest rainfall is extremely different at distances much shorter than the width of the Pan. Read (3) studied this irregularity and showed that it is not possible to correct the height of the water level of the Pan in the forest for rainfall. For a brief period an attempt was made to overcome both these problems by placing a plastic roof at 1.3 meters over the Pan. It prevented litter and rain from falling into the Pan but, unfortunately, also modified radiation and air motion.

The available data were checked subjectively for reliability under the assumption that there would be at least a crude covariation between Pan and Piche data. Many Pan recordings were eliminated from the statistics because of obvious unreliability.

5. COMPARATIVE ANALYSIS

After elimination of errors, the relationship between the two evaporimeters and the differences among locations were studied. The reader must bear in mind that the checked measurements represent the actual evaporation from the instrument. Thus, the word "evaporation" is used synonymously with "measurement." Nothing is known about evaporation that took place elsewhere, and the instrument readings represent only the performance of the instrument. The following analyses are published under the assumption that meaningful relationships between instrument evaporation and natural evaporation can be established.

The comparative analyses are roughly divided into correlative studies of daily and monthly data and correlations between different instruments at the same site, like instruments at the same sites, and like instruments at different sites. It is hoped in this way that the greatest number of scientists in this field can profit from this work.

a Correlation of Daily Evaporation Totals

(1) Like instruments, different stations. Figures 2 and 3 present the correlation between the Standard Pan measurements and the correlation between the Piche measurements, respectively, at the Chiva Chiva and Madden Dam stations for the period December 1966 through April 1967.

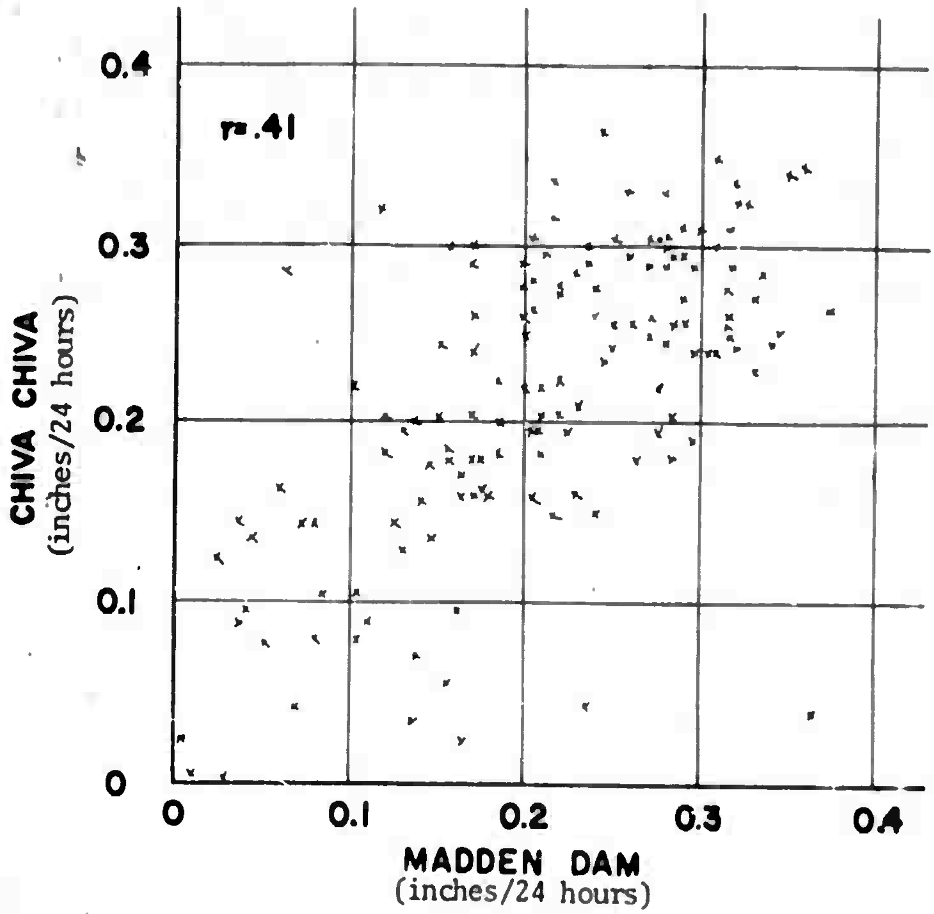


Figure 2. Scatter Diagram of Daily Standard Pan Measurements at Chiva Chiva and Madden Dam

The correlation coefficients are 0.41 between the Pans and 0.55 between the Piches. Whether or not the lower coefficient of the Pan data reflects the general deficiencies of Pan measurements delineated above cannot be decided from the available data. Whatever the reason, Standard Pan results were less reproducible than Piche results. As no conventional meteorological data have been collected at Madden Dam, figures 2 and 3 can be analyzed only superficially by stating that there is a moderate amount of covariation between these stations located 13 miles apart. The two Environmental Data Base stations were closer together and consequently

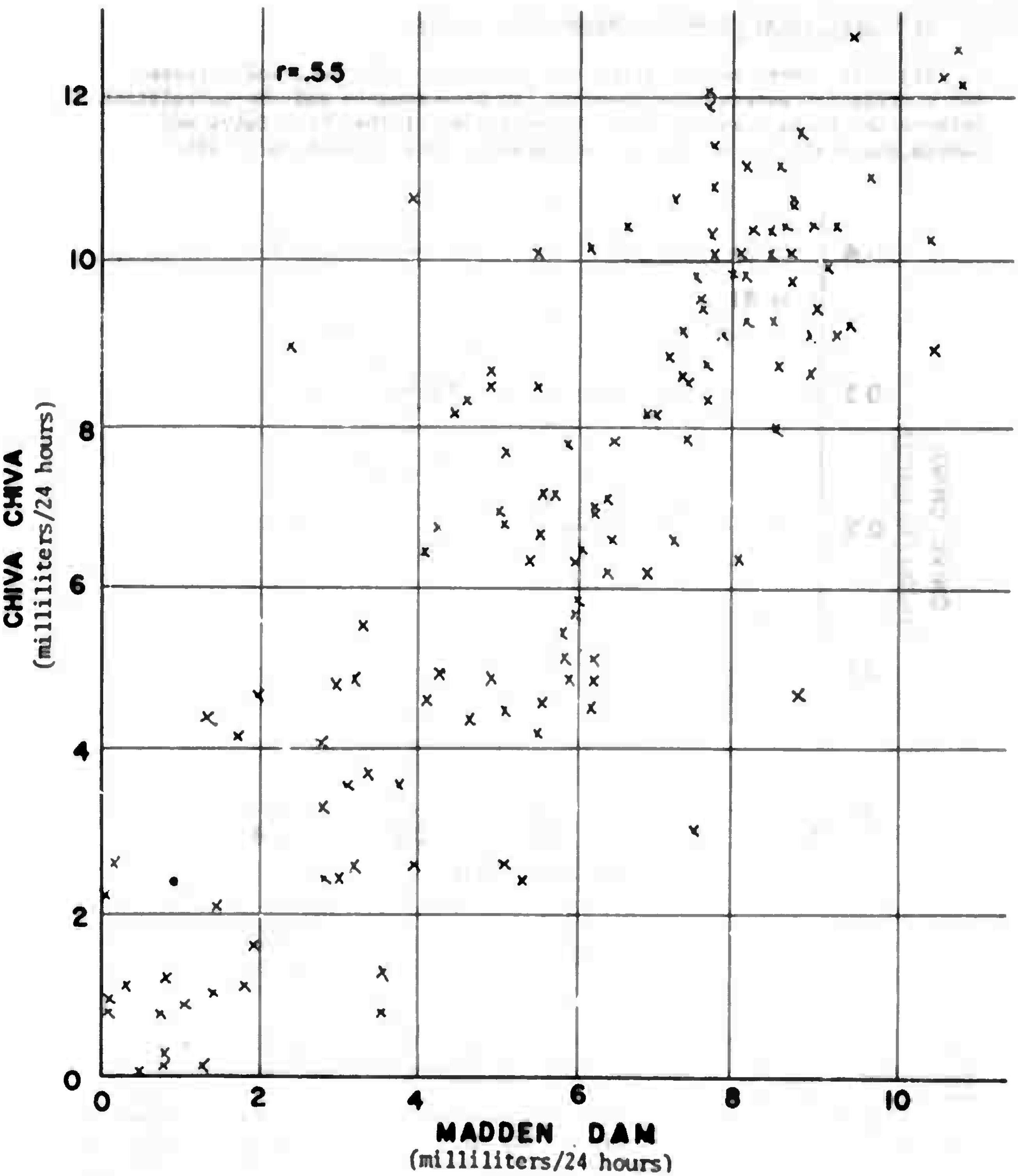
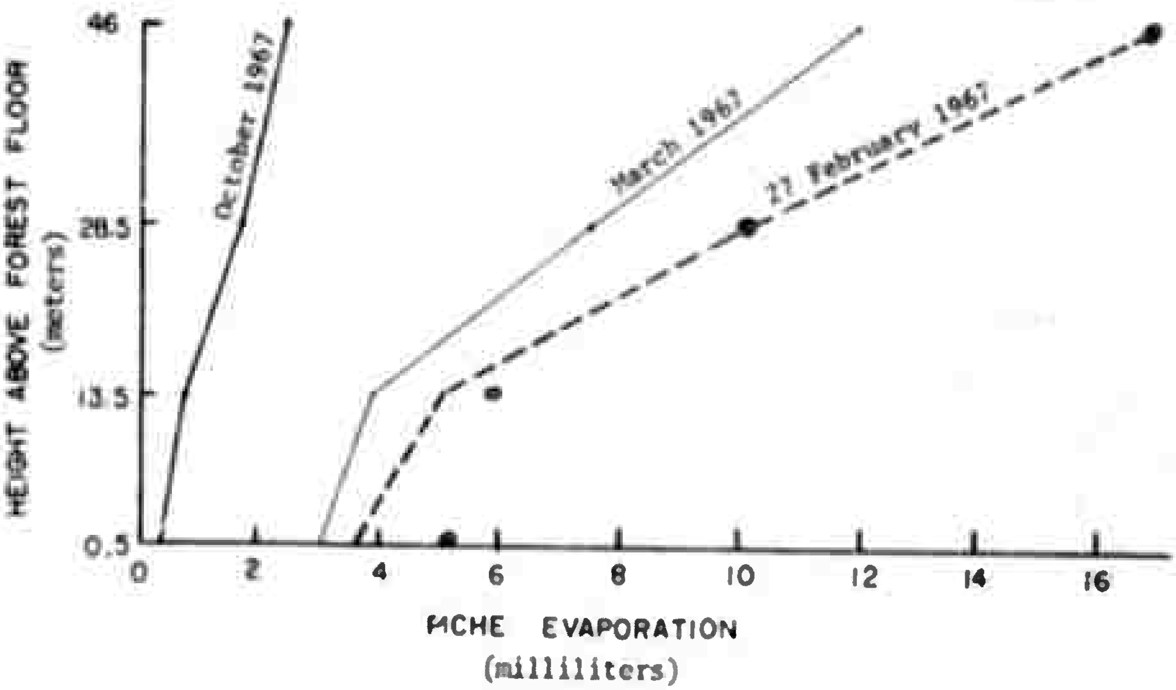


Figure 3. Scatter Diagram of Daily Piche Measurements at Chiva Chiva and Madden Dam

show a stronger association. (Also, it was possible to check the data and eliminate errors.) For example, the Pearson product-moment correlation coefficients between the Piche measurements in Chiva Chiva (near the surface) and the Albrook Forest (at 46 meters over the forest floor) were 0.61 in October 1966 and 0.98 in May 1967. The dry season coefficients were higher than those of the rainy season because the data are dispersed over a wider range and proportionately larger than the observational errors. The greatest dispersion of 24-hour evaporation totals occurs in the transition months between the seasons when dry days with high evaporation rates alternate with damp days with lesser rates. Normally, April and December are transition months. In 1967, when most of these measurements were made, the end of the dry season was delayed until May.

(2) Like instruments, same station. Table I shows that there were always several evaporimeters working on the Albrook tower at the same time. Figure 4 shows that evaporation in the forest increases very much with height (if it is not very close to zero). It presents the vertical distribution of the Piche evaporation of typical months, of an extreme day, and the absolute extreme measured during this project.



LEGEND: ——— = Daily means of extreme months
- - - - = One extreme day
● = Absolute extremes of the level

NOTE: 28.5m is 2m above treetops; 13.5m is the base of the upper canopy.

Figure 4. Piche Evaporation in and above a Tropical Forest

Piche evaporation near the ground can be quite large in a tropical semievergreen forest. The extreme was measured at the beginning of the observation period when the vegetation was reduced by the effects of the tower construction and may or may not occur in undisturbed environments. The March value at 0.5 meter in the forest is very close to the mean summer value measured with the same type of instrument in many places in Germany, with the difference, however, that the German measuremnnts show a much greater dispersion up to an exceptional maximum of 22 milliliters in 24 hours (8). In tropical San Salvador, Central America, the mean daily Piche evaporation oscillated between 2 milliliters in September and 8 milliliters in February measured at an open exposure site over a 5-year period (9). This is close to the values obtained immediately over the forest canopy in Albrook (see table III, page 16).

In spite of the great change of the magnitude of evaporation, the correlation between simultaneous readings at different levels is excellent. In May 1967, for example, the correlation coefficients were:

	46	28.5	13.5	0.5 meters	
46 meters	-	.971	.930	.798	(above the forest)
28.5	-	-	.952	.847	(a short distance above the trees)
13.5	-	-	-	.877	(between the upper and the lower canopy)
0.5	-	-	-	-	(near the forest floor)

These values rise slightly when the inaccuracies of measurement are numerically estimated and then eliminated through simple algebra (4). The greatest improvement is found in the correlation coefficient between the 46- and 0.5-meter levels which rises from 0.798 to 0.822, assuming a mean observational error of 0.1 milliliter. Read (3) concluded from a few measurements that weather changes reach through the canopy down to the forest floor, though reduced in effect. The high correlation coefficients confirm this conclusion with the much greater number of measurements used in this paper. Also the reduction factors derived from the Piche measurements correspond exactly to those found by Read (3) who worked with Livingstone atmometers.*

(3) Different instruments, same station. Three series of data contain simultaneous readings of the Piche evaporimeter and the Standard Pan (table I). The most extensive series was taken at Chiva Chiva where

* The Livingstone is inconvenient because each instrument has a different calibration, and this calibration can change with time through obstruction of the pores by air contaminants. The Livingstone is superior to the Piche only when strip-chart recordings are required.

parallel readings were taken during 26 out of 33 months. Similar readings were taken at Madden Dam during an 11-month period. As explained on page 6, measurements with an open Pan in the forest failed completely. Unconventional Standard Pan measurements were taken simultaneously with Piche readings during a 6-month period when the Pan had a protective plastic roof approximately 1.3 meters over the evaporating water surface.

Very rainy months are not suitable for comparisons of different instruments because the evaporation diminishes to levels that are close in magnitude to the observational errors. Therefore, only data from dry (or relatively dry) months have been used to construct figure 5 which presents scatter diagrams between Piche and simultaneous Pan readings. The scatter makes it impossible to determine if the functional relationship at Chiva Chiva is different from that at Madden Dam; but it can safely be stated that the function for the forest floor is steeper than that for the open site, indicating that the roofed Pan in the forest reacts more slowly than the Pan in the open.

Two explanations are offered for the basic difference of the functional relations in the open and in the forest: (a) The plastic cover and the leaves protect the Pan in the forest from solar radiation and corresponding warming. This is not the case in open exposure where the water in the Pan is being heated during a substantial part of the tropical day. The evaporating surface of the Piche, however, has been shown always to have a temperature close to the wet bulb temperature regardless of the radiation conditions [Roth (5), Mukammal (6)]. Therefore the forest reduces the Pan evaporation more than the Piche evaporation. The effects of radiative warming in the Pan become obvious when hourly measurements are taken. Part II of this report will discuss hourly variations of measured evaporation in detail. (b) The Piche is known to react to wind more than the Pan. This is especially true with low wind speeds; there may be enough wind at the forest floor to affect the Piche, but not enough to have measurable effect on the Pan.

b. <u>Correlation of Monthly Averages</u>

Monthly averages of evaporation were compared between the following sets of data:

(1) In figure 6, Chiva Chiva Piche with Chiva Chiva Pan, and with the Albrook Piches at 0.5, 13.5, and 28.5 meters above ground.

(2) In figure 7, Albrook Piche at 28.5 meters with Chiva Chiva Piche and with the Albrook Piches at 0.5, 13.5, and 46 meters above ground.

There is some duplication in figures 6 and 7 in order to show the functional relationships in different contexts. Each figure is subdivided into two parts with duplication of the curves, again to permit comparison with other curves. All curves were drawn from visual inspection because of the point scatter and the lack of a theory that would call for a certain type of curve. Since the reader may wish to know the actual

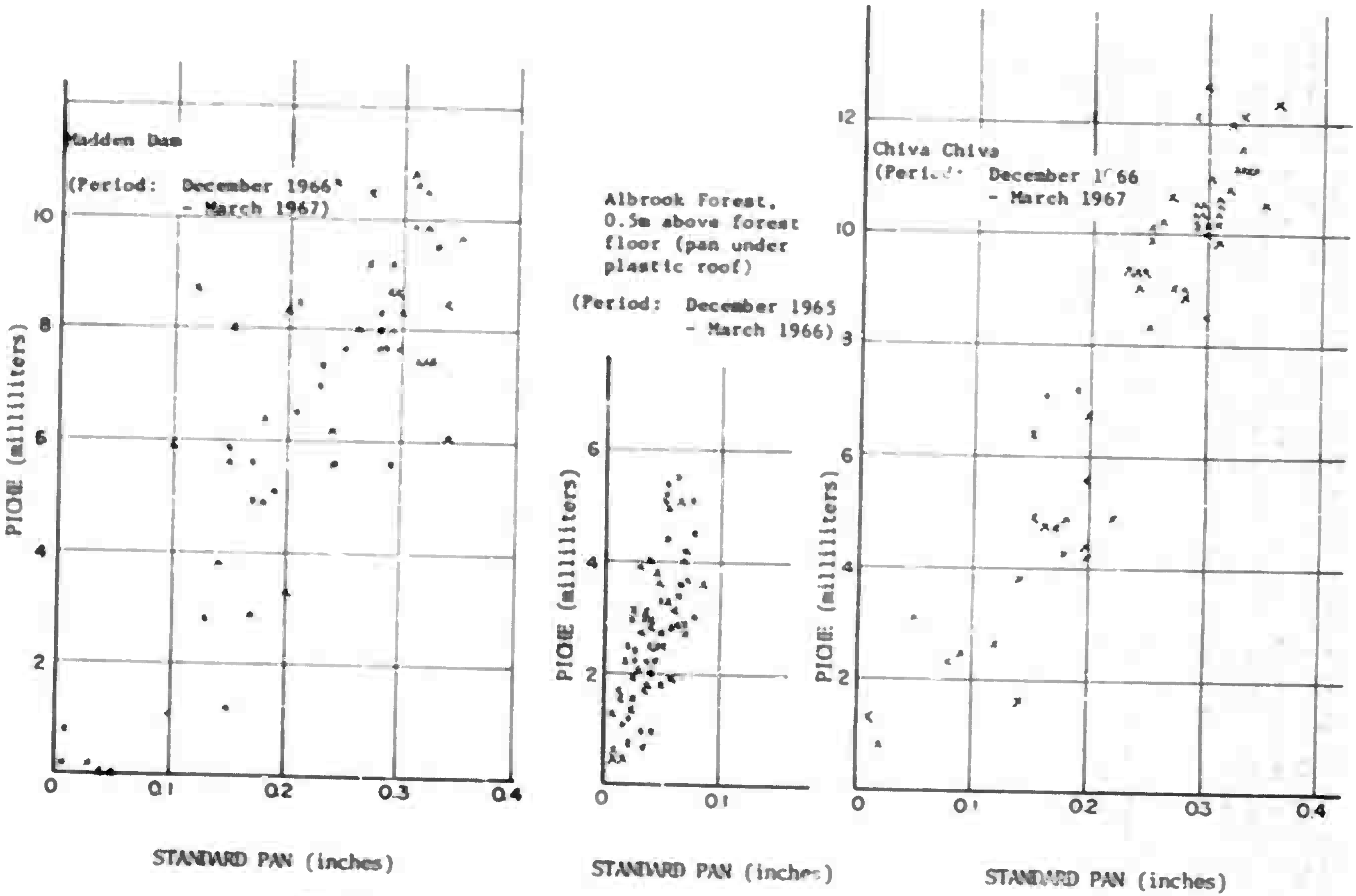
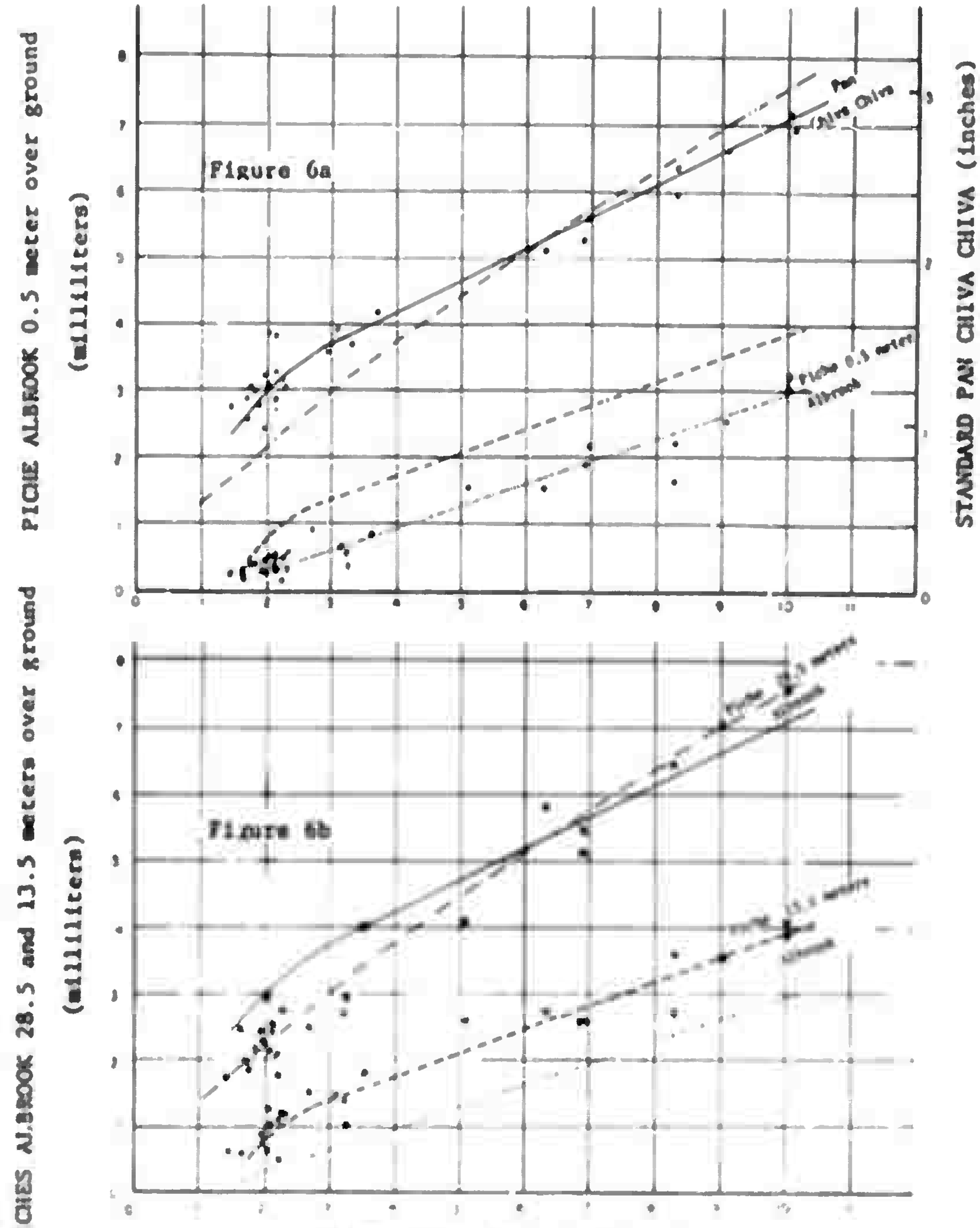


Figure 5. Scatter Diagrams of 24-hour Standard Pan Measurements and Simultaneous Piche Measurements

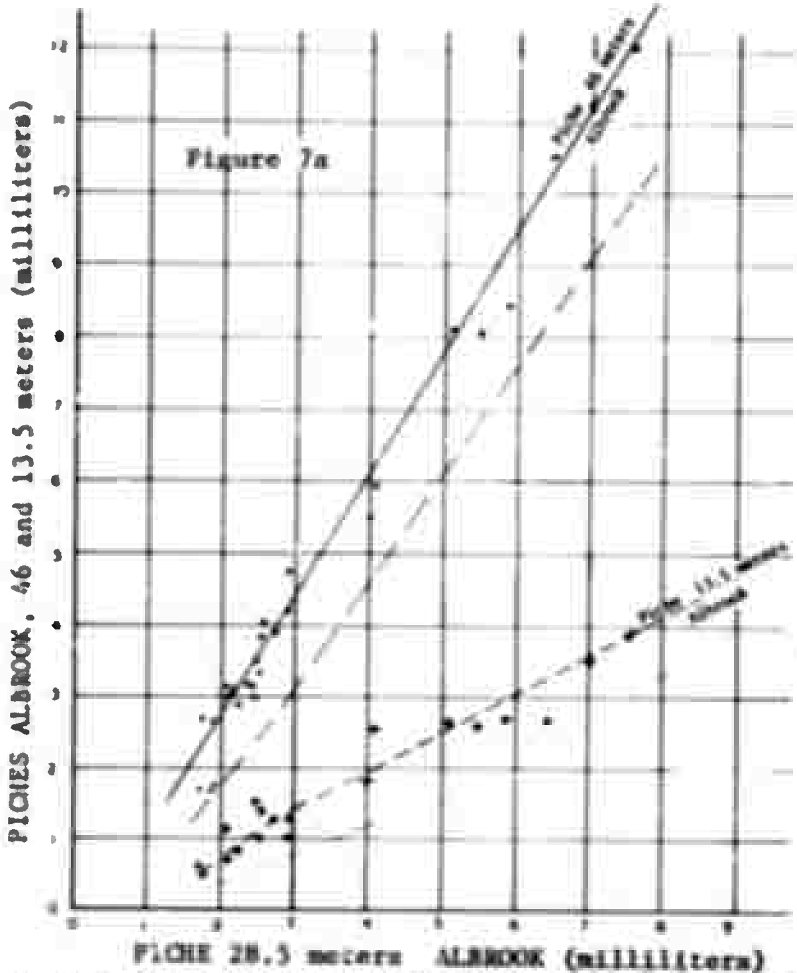


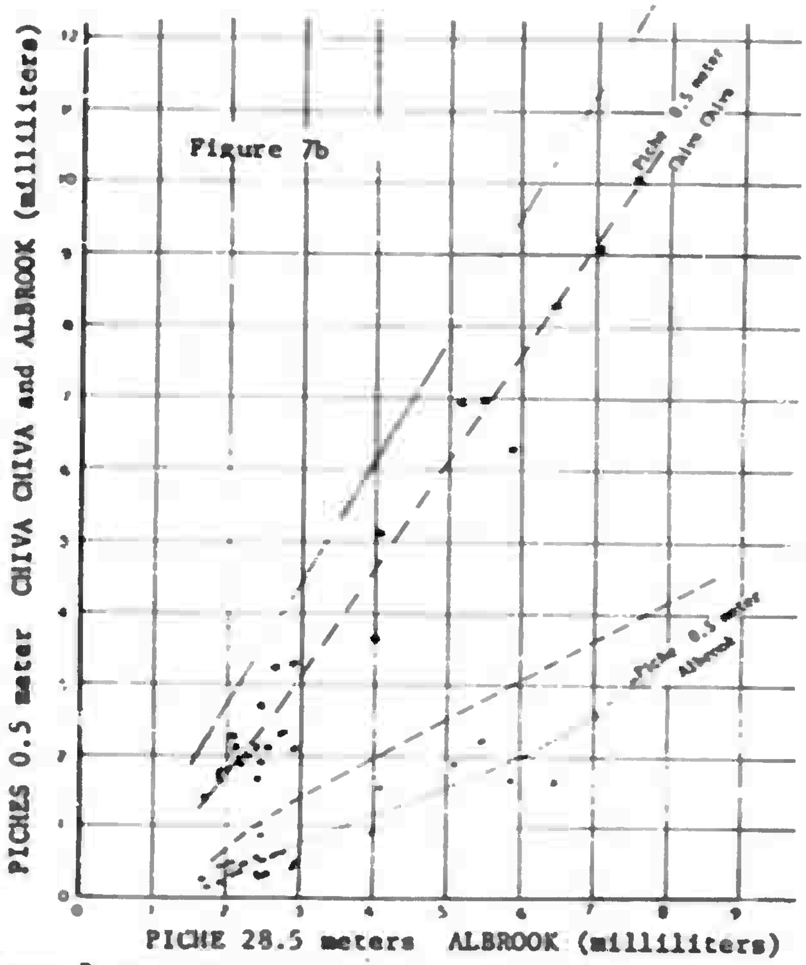
NOTE: The curves fitting the scatter diagrams of figure 6a are repeated in figure 6b and vice versa.

Figure 6a. Scatter Diagrams of Chiva Chiva Piche versus Chiva Chiva Pan (•) and versus Albrook Piche at the Forest Floor (●)

Figure 6b. Scatter Diagrams of Chiva Chiva Piche versus Albrook Piche at 28.5 Meters (✖) versus Albrook Piche at 13.5 Meters (●)

Figure 6. Correlation between Chiva Chiva Piche with Four Other Evaporimeters (Daily Averages of Individual Months)





NOTE: The curves fitting the scatter diagrams of figure 7a are repeated in figure 7b and vice versa.

Figure 7a. Scatter Diagrams of Piche 28.5 Meters Albrook versus Piches Albrook at 46 Meters (-), and 13.5 Meters (+)

Figure 7b. Scatter Diagrams of Piche 28.5 Meters Albrook versus Piches at 0.5 Meters Chiva Chiva (✱) and Albrook (•)

Figure 7. Correlation between Piche Albrook at 28.5 Meters over Ground with Four Other Evaporimeters

scatter, the individual data points have been plotted. Presenting all data points in one figure would have rendered it illegible; therefore, only the data points of two of the four curves of each subfigure have been entered. Figure 6a, for example, contains only the scatter diagrams from which the solid and the short-dashed curves were derived, whereas figure 6b contains the scatter diagrams of the dotted and dash-dotted curves; figures 6a and 6b contain the same four fitted curves.

None of the curves are straight lines through the origin. Since high evaporation values are typical for the dry season and those for the rainy season are small, it follows that proportionality factors between different instruments change during the course of the year. This is also true for straight parts of the curves as long as the extension of the straight lines does not go through the origin. This qualification has been overlooked in several publications of this kind.

It can be deduced from figure 6 that there are months with practically no evaporation at the forest floor and, to a lesser extent, at the base of the canopy while the instruments with free exposure show measurable amounts for all months. Figure 6 also shows that monthly evaporation in the dry season is greater in the forest than it is in the open during the rainy season.

The increase in slope of the curve for the 28.5- versus 46-meter covariation shown in figure 7 is probably the consequence of the greater increase of wind speed with height during the dry season. During that time, the wind speed over the canopy at 46 meters is approximately three times the velocity of that at 28.5 meters. In the rainy season the ratio is closer to 2:1. Similar reasoning may also explain the shape of the curve for the 28.5- versus 13.5-meter levels, while great dispersion of the data from the lowest level obviously allows the drawing of different curves.

c. Annual Variations

The curves of figures 6 and 7 have been used to fill the gaps documented in table I, and from the data completed in this way the annual variations of six instruments have been computed and are listed in tables IIIa and IIIb. Table IIIa presents the data in the units in which they were recorded and table IIIb presents the same data in percent of the respective annual totals. Rainfall data have been added.

Inspection of Table IIIb shows that the annual variations in different surroundings are different. Specifically, the table demonstrates that during the rainy season seasonal changes in the free atmosphere do not so readily penetrate to the ground as do day-to-day changes [paragraph 5a(1)]. No delay with height can be observed in the dry season. As could be expected from previous paragraphs, the Standard Pan has an annual variation that differs from that of the Piche.

TABLE III. ANNUAL VARIATIONS OF EVAPORATION AND RAINFALL (MAY 1965 THROUGH DECEMBER 1967)

a. Monthly and Annual Totals

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	6.4	7.3	8.7	6.5	4.9	3.7	4.1	3.8	3.6	3.7	3.9	4.8	61.4
2	200	244	311	208	110	69	75	64	62	52	59	88	1544
3	259	316	395	243	149	102	108	105	92	84	84	141	2076
4	169	197	243	159	105	72	79	75	66	59	61	93	1377
5	77	100	124	77	56	33	34	34	25	23	21	38	642
6	46	67	98	61	29	16	15	15	10	10	10	16	393
7	0.9	0.3	0.0	4.6	12.3	8.6	9.4	7.8	6.3	13.6	16.0	4.8	84.5
8	1.5	0.3	0.8	5.5	10.0	8.6	7.8	5.3	9.0	13.3	15.2	5.4	82.7

b. Percents of Annual Totals

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	10.4	11.9	14.2	10.6	8.0	6.0	6.7	6.2	5.9	6.0	6.4	7.8	100
2	13.0	15.8	20.2	13.5	7.1	4.5	4.9	4.1	4.0	3.4	3.8	5.7	100
3	12.5	15.2	19.0	11.7	7.2	4.9	5.2	5.0	4.4	4.0	4.0	6.8	100
4	12.3	14.3	17.6	11.5	7.6	5.2	5.7	5.5	4.8	4.3	4.4	6.8	100
5	12.0	15.6	19.4	12.0	8.7	5.1	5.4	5.4	3.8	3.6	3.3	5.9	100
6	11.7	17.1	25.0	15.4	7.5	4.2	3.8	3.8	2.5	2.5	2.5	4.2	100
7	1.0	0.3	0.0	5.4	14.6	10.1	11.1	9.3	7.4	16.1	18.9	5.7	100
8	1.8	0.4	0.9	6.6	12.1	10.4	9.4	6.4	10.9	16.1	18.4	6.5	100

LEGEND:
1 Evaporation (in) Standard Pan, Chiva Chiva
2 Evaporation (ml) Piche, Chiva Chiva
3 Evaporation (ml) Piche, 46m over forest floor, Albrook
4 Evaporation (ml) Piche, 28.5m over forest floor, Albrook
5 Evaporation (ml) Piche, 13.5m over forest floor, Albrook
6 Evaporation (ml) Piche, 0.5m over forest floor, Albrook
7 Rainfall (in) Chiva Chiva
8 Rainfall (in) 46m over forest floor, Albrook (approximately 18m over treetops)

NOTE: Because of rounding-off, the sum of the monthly totals does not always equal the annual total.

There is little correlation between rainfall totals and evaporation totals. The strong double wave which can be observed in the annual variation of rainfall during the measuring period (this double wave is not observed every year) is only faintly reflected in the simultaneous evaporation. On the other hand, the rainfall was close to zero from January through March while the evaporation increased considerably. This low correlation with rain was found for the Pan as well as for the Piche. This result is not surprising because the amount of rainfall depends more on the vertical distribution of meteorological parameters than on the conditions near the ground. Furthermore, evaporation contributes daily to the total, but rainfall contributes only on those days when it rains (which may be only once or not at all during a dry season month).

The correlation coefficient between global radiation (i.e., the sum of direct sun and indirect sky radiation) and evaporation is high; that between wind and evaporation is lower. Table IV shows these coefficients. For global radiation, the Eppley pyrheliometer measurements of the Atmospheric Sciences Laboratory, Canal Zone Meteorological Team at Gun Hill, were used; and for wind, Environmental Data Base recordings at the 26.5-meter level at Chiva Chiva (the only level with such recordings throughout the entire period).

TABLE IV. CORRELATION COEFFICIENTS BETWEEN MONTHLY TOTALS (MEANS) OF EVAPORATION WITH RADIATION AND WIND SPEED FOR 31 MONTHS AT CHIVA CHIVA

	Global Radiation	Wind	Radiation Corrected for Wind	Wind Corrected for Radiation	Radiation Plus Wind
Standard Pan	.915	.884	.689	.515	.938
Piche	.908	.879	.658	.543	.936

It was necessary to correct the raw coefficients (columns 1 and 2 of table IV) because wind and radiation have similar annual variations. The corrected coefficients are given in columns 3 and 4. Column 5 presents the correlation coefficients between the measured monthly totals of evaporation and those computed from regression equations. The regression equations were:

$$100\ SP = 0.4051(R-393) + 0.8342(W^2-27.9) + 1.60$$
$$10\ Pi = 0.6661(R-393) + 1.7564(W^2-27.9) + 1.41$$

where SP = monthly Pan evaporation in inches
Pi = monthly Piche evaporation in milliliters
R = mean daily global radiation in langleys
W = mean monthly wind speed in mph

The ratios between the factors are 0.8342/0.4051 = 2.0592 for the Pan, and 1.7564/0.6661 = 2.6366 for the Piche. This indicates that the Piche is more sensitive to wind than the Pan. The difference, however, is not so great as to justify the statement that "...the Piche is very sensitive to wind speed..." (7). Similar exaggerated statements can be found in many textbooks on meteorological instruments.

The ratios of the factors in the regression equations do not change much when W is used instead of W^2; in this case the correlation coefficients of the last column of table IV become a little smaller.

Table IV and the regression equations refer to monthly means and totals, respectively. Daily values of evaporation depend in a different way on meteorological parameters. In the Canal Zone the daily amount of evaporation is almost completely determined by the global radiation. This does not mean that the radiation alone produces evaporation, but rather that all elements that effect evaporation are highly correlated with the radiation. This is not true in colder regions of the world where a sunny day may be very cold and a cloudy day warmer.

Table V lists correlations between different meteorological parameters and evaporation on a daily basis, measured in the open field of Chiva Chiva or nearby Gun Hill, during February and March 1967.

TABLE V. CORRELATION COEFFICIENTS BETWEEN DIFFERENT PARAMETERS (BASED ON DAILY VALUES OBTAINED AT THE OPEN SITE, FEBRUARY AND MARCH 1967)

	W(1/3)	W(1/2)	W(2/3)	W(5/6)	W(1)	F	E	D	C	B	A	Pi
SP	.731	.727	.720	.711	.701	.739	-.830	-.553	.763	.708	.903	.949
Pi	.714	.711	.706	.698	.689	.746	-.849	-.575	.721	.604	.819	
A	.663	.655	.644	.633	.619	.676	-.790	-.503	.751	.841		
B	.543	.534	.524	.513	.501	.695	-.674	-.289	.686			
C	.696	.682	.667	.650	.631	.843	-.817	-.388				
D	-.460	-.457	-.453	-.448	-.441	(-.417)	.625					
E	-.657	-.646	-.633	-.618	-.602	-.894						
F	.609	.596	.581	.566	.549							
W (1)	.978	.987	.995	.999								
W (5/6)	.985	.994	.999									
W (2/3)	.993	.998										
W (1/2)	.998											

LEGEND:
- SP Standard Pan (inches/day)
- Pi Piche evaporimeter (milliliters/day)
- A Total global radiation, measured with an Eppley pyranometer, total of all hours (langleys)
- B Global radiation, the hour with the highest total (langleys)
- C Temperature maximum (°F)
- D Dew Point, daily mean (°F)
- E Minimum of relative humidity (percent)
- F Maximum soil surface temperature, measured with an infrared thermometer (°F)
- W() Mean daily wind speed, elevated to the power indicated in parentheses, e.g., W (1/2) = square root of the mean speed (miles per hour)

The best-fit curves derived from the correlation matrix are -

for the Standard Pan:

$$SP = 0.00051A - 0.00139B - 0.00283E + 0.00357W + 0.198$$
(correlation coefficient with measured values: .947)

for the Piche:

$$Pi = 0.01710A - 0.08993B - 0.17127E + 0.15425W + 13.877$$
(correlation coefficient with measured values: .924)

All coefficients but those in parentheses are significant at the 0.001 level. It is interesting to note that in the multiple regression the wind speed to the power one gives the best results, whereas the individual correlations between wind and any other variable become higher with decreasing powers. It is of further interest that the regression equations are not improved by inclusion of the temperature. Obviously, the high correlations between temperature and radiation and relative humidity have the effect of eliminating temperature from the equation. This finding is in contrast with findings of conditions outside the tropics, but seems to be typical for a warm climate without considerable seasonal changes of temperature.

6. CONCLUSIONS

This paper closes a gap in climatological information. Monthly mean evaporation data are presented for a Standard Pan at an open site and compared with Piche atmometers at the same site as well as in and above a tropical forest. Analysis of daily data is summarized as follows:

a. During tropical rains a substantial part of the water in the Standard Pan may splash out so that measurements indicate much higher evaporation values than actually occurred. A Piche should be used along with each Standard Pan to detect and eliminate erroneous data.

b. Simultaneous Piche measurements at different stations show closer mutual association than simultaneous Pan measurements.

c. Piche measurements show close association in the rainy season at a tropical open site and excellent association in the dry season above a tropical forest. Although the average evaporation increases substantially with height within the forest, the correlation coefficients between different levels are high, e.g., 0.822 between 0.5 and 46 meters over ground. These relationships are obscured in very moist months when the range of actual evaporation is reduced to the magnitude of the observational errors.

d. Best-fit curves between Piche and Standard Pan measurements are not straight lines going through the origin. This explains the local and seasonal changes of the ratio between the two instruments as reported by numerous authors.

e. The use of Pan-type evaporimeters is not desirable in forests because of local irregularity of rain and because of debris falling into the Pan. A Pan exposed in an unconventional way (in a forested area through utilization of a roof) yields lower evaporation rates than uncovered Pans in open areas at times when Piche evaporimeters yield the same results for forested and open sites.

f. The total annual Piche evaporation in the open was 1544 milliliters; that of the Pan, 61.4 inches = 1560 millimeters. During a year the Piche evaporated 2076 milliliters 18 meters over the forest canopy and 393 milliliters at the forest floor.

g. Through regression techniques the monthly evaporation totals can be "explained" mainly through radiation and wind. The regression curves contain the square of the wind speed and show a higher sensitivity of the Piche to wind, but not as much as generally assumed. For the "explanation" of daily evaporation totals, the daily minimum of relative humidity must be added in the regression equations.

Part II of this publication will present the results of hourly comparisons among different types of evaporimeters and will relate these differences to physical characteristics of the instruments.

SECTION B. APPENDICES

APPENDIX I. REFERENCES

1. Berényi, Dénes, *Mikroklimatologie* (Microclimatology), Gustav Fischer Verlag, Stuttgart, Germany (1967) (Translation of the 1965 Hungarian Edition into German) 328p (Quotation refers to p 257)

2. United States Army Tropic Test Center, *Environmental Data Base for Regional Studies in the Humid Tropics, Final Report*, Fort Clayton, Canal Zone, 93p (1970)

3. Read, R.G. "Evaporative Power in the Tropical Forest of the Panama Canal Zone," *Journal of Applied Meteorology*, Vol 7, 414-424 (1968)

4. Portig, W.H., "Messgenauigkeit und Korrelationskoeffizient" (Accuracy of Measurement and Coefficient of Correlation), *Annalen der Hydrographie und Maritimen Meteorologie*, Vol 64, 2nd Köppen-Heft, 32-37 (1936)

5. Roth, R., "Konstruktive und Thermodynamische Eigenschaften des Piche-Evaporimeters" (Constructive and Thermodynamical Properties of the Piche Evaporimeter), *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B*, Vol 11, 108-125 (1961)

6. Mukammal, E.I., "Evaporation Pans and Atmometers," *Proceedings of Hydrology Symposium No. 2 (Evaporation)*, National Research Council of Canada, p 84-99 (1961)

7. Middleton, W.E.K., and Spilhaus, A.F., *Meteorological Instruments*, University of Toronto Press, 3rd edition, 286p (quotation refers to p 133) (1953)

8. Uhlig, Siegfried, "Bestimmung des Verdunstungsanspruchs der Luft mit Hilfe von Piche-Evaporimetern," (Measurement of the Evaporative Power of the Air by Means of Piche Evaporimeters), *Mitt. d. Deutschen Wetterdienstes*, Vol 2, No 13 (1955)

9. Lessmann, Helmut, then Director of the Meteorological Service of El Salvador, Personal Correspondence, 4 September 1964

-21-